Lessons from Ten Years of Nanotechnology Bibliometric Analysis

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Abstract

This paper summarizes the 10-year experiences of the Program in Science, Technology, and Innovation Policy (STIP) at Georgia Institute of Technology (Georgia Tech) in support of the Center for Nanotechnology in Society at Arizona State University (CNS-ASU) in understanding, characterizing, and conveying the development of nanotechnology research and application. This work was labeled "Research and Innovation Systems Assessment" or (RISA) by CNS-ASU.

RISA concentrates on identifying and documenting quantifiable aspects of nanotechnology, including academic, commercial/industrial, and government nanoscience and nanotechnology (nanotechnologies) activity, research, and projects. RISA at CNS-ASU engaged in the first systematic attempt of its kind to define, characterize, and track a field of science and technology. A key element to RISA was the creation of a replicable approach to bibliometrically defining nanotechnology. Researchers in STIP, and beyond, could then query the resulting datasets to address topical areas ranging from basic country and regional concentrations of publications and patents, to findings about social science literature, environmental, health, and safety research and usage, to study corporate entry into nanotechnology, and to explore application areas as special interests arose. Key features of the success of the program include:

- Having access to "large-scale" R&D abstract datasets
- Analytical software
- A portfolio that balances innovative long-term projects, such as webscraping to understand nanotechnology developments in small and medium-sized companies, with research characterizing the emergence of nanotechnology that more readily produces articles
- Relationships with diverse networks of scholars and companies working in the nanotechnology science and social science domains
- An influx of visiting researchers
- A strong core of students with social science, as well as some programming background
- A well-equipped facility and management by the principals through weekly problem-solving meetings, mini-deadlines, and the production journal articles rather than thick final reports.

Background

The 21st Century Nanotechnology Research and Development Act of 2003 (Public Law 108-153, U.S. Congress (Dec. 2003)) was the genesis of what became the Center for Nanotechnology in Society at Arizona State University (CNS-ASU). The act provided a framework for nanotechnology research, encouraged application of nanotechnology for industrial competitiveness, provided for education and training, and required that ethical, legal, environmental, and other societal concerns to be addressed. The focus of the later was Section 2(b)(10), which called for the creation of a societal implications research program, required that nanoscale science and engineering centers (NSECs) to address societal implications, called for the integration of societal concerns with nanotechnology R&D, sought to ensure that advances in nanotechnology would lead to quality of life improvements for all, and provided for public input into the process.

The US National Science Foundation would administer these awards based on a merit-review process. After a competitive process, NSF funded two NSECs devoted to the examination of societal issues: CNS-ASU and the Center for Nanotechnology in Society at the University of California at Santa Barbara. In addition, there were Nanoscale Interdisciplinary Research Teams supported at the University of South Carolina, Michigan State University, and Harvard/University of California at Los Angeles/National Bureau of Economic Research, the latter of which is charged to create a NanoBank to compile quantitative information about patents, publications, information of a legal/ethical nature, and other documents. There also were individual project awards to social scientists. At its height, what became the US National Nanotechnology Initiative allocated nearly 3% of its budget to societal considerations.

The two societal NSECs were funded from 2005 to 2015, a period comprised of an initial five years, a renewal five years, and a "no cost extension" year. CNS-ASU received $6.2 million in the first five-year period and $6.5 million in the second period. The program in Science, Technology, and Innovation Policy (STIP) at Georgia Institute of Technology (Georgia Tech) in Atlanta, Georgia USA was a key partner in CNS-ASU. Other CNS-ASU partner institutions were the University of Wisconsin at Madison, Rutgers University, University of Georgia, North Carolina State University, and the University of Colorado. Of this list, Georgia Tech and University of Wisconsin were the only two partners to formally receive CNS-ASU money throughout the 10 years. The STIP group at Georgia Tech, which was anchored by four senior researchers and students (undergraduate, masters, and doctoral students), received $726,000 in the first five years and $650,000 in the second five years.

The Georgia Tech partnership with ASU was built around several of the Georgia Tech team members having known the ASU team for many years prior to the center's creation. The winning CNS-ASU proposal was structured around a paper that two of the ASU principals -Dave Guston and Dan Sarewitz—had published in *Technology and Society* titled "Real Time Technology Assessment."[1] One of the methodologies proposed in this paper was grounded in the use of bibliometrics to understand the trajectory of an emerging technology. This methodology formed the core role that the STIP team was to play in the center through what eventually became known as Research and Innovation Systems Assessment (RISA). RISA involves characterizing the nanotechnology enterprise and its dynamics through data-mining techniques such as bibliographic database analysis (yielding bibliometric data) and patent database analysis (yielding intellectual property data), as well as through text-mining, interviews, and other research methods.

The design of RISA, by the STIP principals, was straightforward in nature. RISA asked the questions: "who is doing what in nanotechnology; when, where, and with what implications"? RISA had two main parts: the first involved assessment of the research system and the second, of the enterprise

[1] Guston, D. H., & Sarewitz, D. (2002). Real-time technology assessment. *Technology in society*, *24*(1), 93-109.

system. In the sometimes jargon-laden world of social science research, this structure was helpful, in communicating results, including to the external review panel charged with evaluating the performance of the center. It also was sufficiently accommodating to give the team flexibility to pursue "hot" topics as they emerged.

Research Contributions

A foundational resource and contribution of the STIP nano effort was the creation of a search algorithm to operationally define nanotechnology. The principals originally sought access to the UCLA NanoBank for such data, but found that was unworkable in the timeframe needed, so the team began to develop a search strategy. One key feature of the search was, first, the use of keywords linked by Boolean operators that extended beyond the conventional (at the time) use of wildcard versions of nano-prefixed terms only to include terms relating to nanoparticles, processes, microscopy, molecular level developments, journals, and (in the case of patents) designated cross-classes for the field. Second, the search involved a multi-stage process in which the second stage eliminated out-of-domain terms associated with size or non-engineered phenomena alone.[2] And third, unlike many definitions of an emerging technology, the STIP group tested the terms used in the search several years later to determine the extent to which modifications to the initial search tool improved its precision and recall.[3] Table 1 presents the core search (not showing the routines to exclude non-nano items).These results were validated with dozens of experts in the field through surveys and in-person interviews. Affiliation with CNS-ASU gave the STIP group access to experts that it would not have had on its own.

Table 1. The Core Georgia Tech Nano Search Strategy

Search	Contingency	Terms
1. Nano*	No	TS = (nano*)
2. Quantum	No	TS = ((“quantum dot*” OR “quantum well*” OR “quantum wire*”) NOT nano*)
3. Self-assembly	Yes, MolEnv-I	TS = ((“self assembl*” OR “self organiz*” OR “directed assembl*”) AND MolEnv-I)
4. Nano-related	No	TS = ((“molecul* motor*” OR “molecul* ruler*” OR “molecul* wir*” OR “molecul* devic*” OR “molecular engineering” OR “molecular electronic*” OR “single molecul*” OR fullerene* OR **buckyball** OR **buckminsterfullerene** OR **C60** OR **“C-60”** OR **methanofullerene** OR **metallofullerene** OR **SWCNT** OR **MWCNT** OR “coulomb blockad*” OR bionano* OR “langmuir–blodgett” OR Coulombstaircase* OR “PDMS stamp*” OR **graphene** OR **“dye-sensitized solar cell”** OR **DSSC** OR **ferrofluid*** OR **“core–shell”**) NOT nano*)
5. Microscopy and spectroscopy	Yes, MolEnv-R	TS = ((((TEM or STM or EDX or AFM or HRTEM or SEM or EELS or **SERS** or **MFM**) OR “atom* force microscop*” OR “tunnel* microscop*” OR “scanning probe microscop*” OR “transmission electron microscop*” OR “scanning electron microscop*” OR “energy dispersive X-ray” OR “xray photoelectron*” OR **“x-ray photoelectron”** OR “electron energy loss spectroscop*” OR **“enhanced raman-scattering”** OR **“surface enhanced raman scattering”** OR **“single molecule microscopy”** OR **“focused ion beam”** OR **“ellipsometry”** OR **“magnetic force microscopy”**) AND MolEnv-R) NOT nano*)
6. Nano-pertinent	Yes, MolEnv-I	TS = (((NEMS OR Quasicrystal* OR “quasi-crystal*” OR **“quantum size effect”** OR **“quantum device”**) AND MoleEnv-I) NOT nano*)
7. Nano-pertinent	Yes, MolEnv-R	TS = (((biosensor* OR NEMS OR (“sol gel*” OR solgel*) OR dendrimer* OR **CNT** OR “soft lithograph*” OR **“electron beam lithography”** OR **“e-beam lithography”** OR “molecular simul*” OR **“molecular machin*”** OR **“molecular imprinting”** OR “quantum effect*” OR **“surface energy”** OR “molecular sieve*” OR “mesoporous material*” OR **“mesoporous silica”** OR **“porous silicon”** OR **“zeta potential”** OR **“epitax*”**) AND MolEnv-R) NOT nano*)
8. Nano journals	No	SO = ((Fullerene* OR IEEE Transactions on Nano* OR Journal of Nano* OR Nano* OR Materials Science Engineering C* OR **ACS Nano** OR **Current Nanoscience** OR **Digest Journal of Nanomaterials and Biostructures** OR **IEE Proceedings Nanobiotechnology** OR **IET Nanobiotechnology** OR **International Journal of Nanomedicine** OR **International Journal of Nanotechnology** OR **Journal of Biomedical Nanotechnology** OR **Journal of Computational and Theoretical Nanoscience** OR **Journal of Experimental Nanoscience** OR **Nature Nanotechnology** OR **Photonics and Nanostructures*** OR **Wiley Interdisciplinary Reviews Nano***) NOT nano*)
Total		1 or 2 or 3 or 4 or 5 or 6 or 7 or 8

Source: See footnote 2.

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[2] Alan L. Porter, Jan Youtie, Philip Shapira, David J. Schoeneck. 2008. Refining Search Terms for Nanotechnology. *Journal of Nanoparticle Research* 10:715-728. doi: 10.1007/s11051-007-9266-y

[3] Sanjay Arora, Alan L. Porter, Jan Youtie, Philip Shapira. 2013. Capturing Developments in an Emerging Technology: An Updated Search Strategy for Identifying Nanotechnology Research Outputs. *Scientometrics* 95(1):351-370. doi: 10.1007/s11192-012-0903-6

The search tool enabled maintenance of datasets of 1.6 million publication metadata records from the Web of Science (WoS; through 2015) and 200,000 patent metadata records from PatStat. Figure 1 presents the distribution of WoS publication trends for the leading countries. We have generated many analyses that address "who, what, where, and when?" questions about nano R&D funding, outputs (publications & patents), and impacts (citations) from the metadata records.[4]

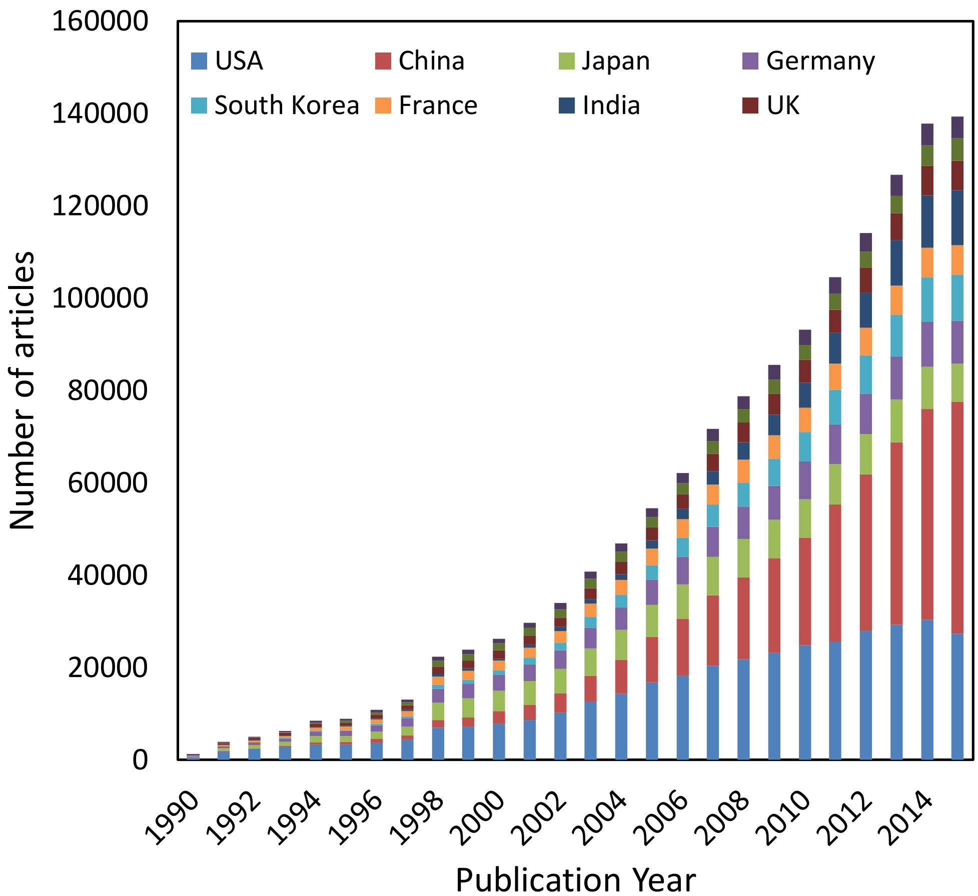

Figure 1. Nano Research Publication by Leading Countries (Georgia Tech search in Web of Science)
Source: See footnote 25

One finding that emerged from this process was that, in the early stages of a field, there was not a standardized terminology about the field. However, we found that terms became more standardized toward the end of the second decade of the nanotechnology's emergence.[5]

In addition to analyzing publications and patents, we also worked with new data sources to understand the larger scientific and commercial emergence of nanotechnology. We performed an analysis of curriculum vita of leading scholars in nanotechnology and compared their trajectory with those in human genetics in both the US and Europe. Data extracted from these curriculum vita showed

[4] See, for example, P. Shapira and J. Wang. "Follow the Money." What was the impact of the nanotechnology funding boom of the past ten years? *Nature*, 2010, 468, 627-628.

[5] Sanjay K. Arora, Jan Youtie, Stephen Carley, Alan L. Porter, Philip Shapira. 2014 (Jan.). Measuring the Development of a Common Scientific Lexicon in Nanotechnology*. Journal of Nanoparticle Research*, 16:2194.

that a more multi-sectoral, multi-disciplinary approach worked better in the US, while a more focused approach worked better in Europe.[6]

In this same vein, we developed a process for gathering and analyzing data on small and medium-sized company websites (webscraping). Webscraping involved accessing, extracting, and coding data not only from the current company websites but also from older websites archived in the Wayback Machine, which enabled us to track company changes over time and eventually to associate it with changes in company performance.[7] Webscraping is an important tool because companies involved with an emerging technology do not always publish and patent their work, but particularly small and medium-size companies do appear to maintain their websites to appeal to investors, government grants, and customers.

The STIP group also advanced knowledge about nanotechnology commercialization in the United States and internationally, through bibliometric and patent analysis methods, but also through the creation of a nanotechnology corporate panel data set. A corporation was included in this panel by virtue of its having had nanotechnology publications authored by or co-authored by an individual in a corporate enterprise, and/or by virtue of having a nanotechnology patent assigned to that corporate entity. We called this "corporate entry." We used our publication and patent datasets, extracted articles authored by private companies and patents assigned to private companies, grouped these, and developed a corporate panel including only those companies having at least four publications or patents. The panel itself grew by 34% from the 1990-2009 period to the update period through 2014, comprising nearly 24,000 corporations in that period. The corporate panel was used in national reviews of the US National Nanotechnology Initiative (NNI). It was also used to examine the growth of companies involved in nanotechnology, especially small and medium-sized corporate enterprises, which comprised an increasingly larger share of patents over time, from 30% in 1990 to 50% by 2009.[8] Another outcome involved the ability to track different strategic approaches for small and medium-sized corporate entry into nanotechnology: one with a more research orientation and a second focused more on product development and patenting. [9]

We used this information about research and companies to delve into several specific nano-enabled application areas:

- An energy technology (Dye-Sensitized Solar Cells -- DSSCs)
- A biomedical technology (Nano-Enabled Drug Delivery -- NEDD), reaching into study of its roles in cancer treatment, and further into brain diseases
- A general purpose technology (GPT) – graphene
- Applications of nanotechnology in the building construction sector.

Our analyses of these application areas suggest that the path to adoption of nano-enabled commercial applications is not smooth. In graphene, the discovery-to application cycle is accelerated and rapidly globalized, but growth patterns vary in different application areas.[10] Drug delivery follows a pattern in

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[6] Youtie, J., Rogers, J., Heinze, T., Shapira, P., & Tang, L. (2013). Career-based influences on scientific recognition in the United States and Europe: Longitudinal evidence from curriculum vitae data. *Research Policy*, *42*(8), 1341-1355.

[7] Arora, S. K., Li, Y., Youtie, J., & Shapira, P. (2015). Using the Wayback machine to mine websites in the social sciences: A methodological resource. *Journal of the Association for Information Science and Technology*.

[8] Youtie, J., & Kay, L. (2014). Acquiring nanotechnology capabilities: role of mergers and acquisitions. *Technology Analysis & Strategic Management 26*(5), 547-563.

[9] Kay, L., Youtie, J., & Shapira, P. (2014). Signs of things to come? What patent submissions by small and medium-sized enterprises say about corporate strategies in emerging technologies. *Technological Forecasting and Social Change*, *85*, 17-25.

[10] Shapira, P., Youtie, J., & Arora, S. (2012). Early patterns of commercial activity in graphene. *Journal of Nanoparticle Research*, *14*(4), 1-15. doi: 10.1007/s11051-012-0811-y

which nano-enabled delivery platforms are grafted onto current pharmaceuticals, rather than leading to co-development or multi-functional approaches.[11] Likewise, dye-sensitized solar cells offer unique advantages, but compare less favorably with incumbent technologies on energy conversion efficiency and long-term stability.[12,13,14] The building construction sector could benefit greatly from manufactured nanotechnology products, but although awareness of these products is higher than expected, adoption of these products is limited by issues around the applicability of these products to project-based outcomes.[15]

We offer a selection of illustrations from these nano-based application areas to show the synergistic advance of methodological capabilities via interesting applications. Figure 2 offers a schematic of the analysis process used to extract key topics from the set of NEDD patents. Figure 3 shows those 13 topics advancing across technology system maturation stages and time periods.[16] We have also recognized that sub-system level analyses are vital to understand technological development. Figure 1c shows a breakout of NEDD into sub-systems for further analyses.[17] It can be informative to plot R&D activity trends for component technologies in each sub-system (not shown here – see appendix).[18]

Figure 4 illustrates a means to probe for technology opportunities. Here we have arrayed a subset of the NEDD technologies identified from our literature search against a subset of the drugs being delivered for brain cancer to illustrate the principle of using co-occurrence of terms in records to indicate likely association. We explore "gaps" further to see if those could represent unexplored opportunities (e.g., to consider trying a given delivery agent for a drug not reported in the literature). We also examined literature cross-citation to examine how research on brain cancer connects with research on Alzheimer's disease. The premise is that since treatment of both confronts the blood-brain barrier, there could be opportunities to enrich awareness of NEDD capabilities across those fields.[19]

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[11] Xiao Zhou, Alan L. Porter, Douglas K. R. Robinson, Min Suk Shim, Ying Guo. Nano-enabled Drug Delivery: A Research Profile. *Nanomedicine*. 2014 Jul; 10(5):889-96. doi: 10.1016/j.nano.2014.03.001

[12] Ying Guo, Chen Xu, Lu Huang, Alan L. Porter. 2012. Empirically Informing a Technology Delivery System Model for an Emerging Technology: Illustrated for Dye-sensitized Solar Cells. *R & D Management* 42(2):133-149. doi: 10.1111/j.1467-9310.2012.00674.x

[13] Xiao Zhou, Alan L. Porter, Douglas K. R. Robinson, Min S. Shim, Ying Guo. 2014 (July). Nano-enabled Drug Delivery: A Research Profile. *Nanomedicine*. 10(5):889-96. doi: 10.1016/j.nano.2014.03.001

[14] Tingting Ma, Alan L. Porter, Ying Guo, Jud Ready, Chen Xu, Lidan Gao. 2014. A Technology Opportunities Analysis Model: Applied to Dye-sensitised Solar Cells for China. *Technology Analysis & Strategic Management* 26(1):87-104.

[15] Sanjay Arora, Rider W. Foley, Jan Youtie, Philip Shapira, Arnim Wiek. 2014. Drivers of Technology Adoption: The Case of Nanomaterials in Building Construction. *Technological Forecasting and Social Change* 87(7). doi: http://dx.doi.org/10.1016/j.techfore.2013.12.017

[16] Ma, J., & Porter, A. L. (2015). Analyzing patent topical information to identify technology pathways and potential opportunities. *Scientometrics, 102*(1), 811-827, doi:10.1007/s11192-014-1392-6.

[17] Zhou, X., Porter, A.L., Robinson, D.K.R., Shim, M.S., and Guo, Y. (2014), Nano-enabled drug delivery: A research profile, *Nanomedicine: Nanotechnology, Biology and Medicine.* 10 (5), 889-896. *http://dx.doi.org/10.1016/j.nano.2014.03.001*

[18] Ma, T., Porter, A. L., Guo, Y., Ready, J., Xu, C., & Gao, L. (2013). A technology opportunities analysis model: applied to dye-sensitised solar cells for China. *Technology Analysis & Strategic Management*, 26(1), 87-104.

[19] Ma, J., Porter, A. L., Aminabhavi, T. M., & Zhu, D. (2015). Nano-enabled drug delivery systems for brain cancer and Alzheimer's disease: research patterns and opportunities. *Nanomedicine: Nanotechnology, Biology and Medicine, 11*(7), 1763-1771, doi:10.1016/j.nano.2015.06.006.

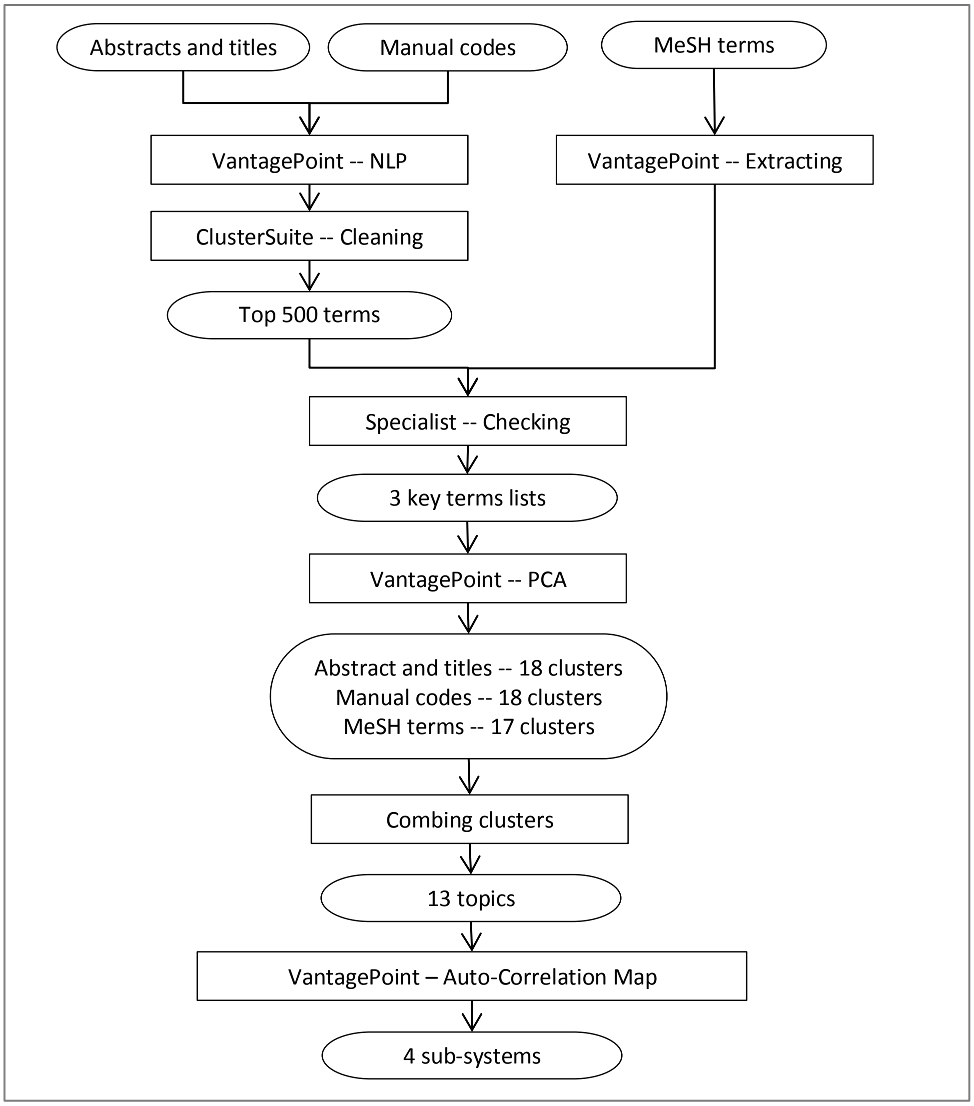

Figure 2. Patent Topical Analysis Process
Source: see footnote 11.

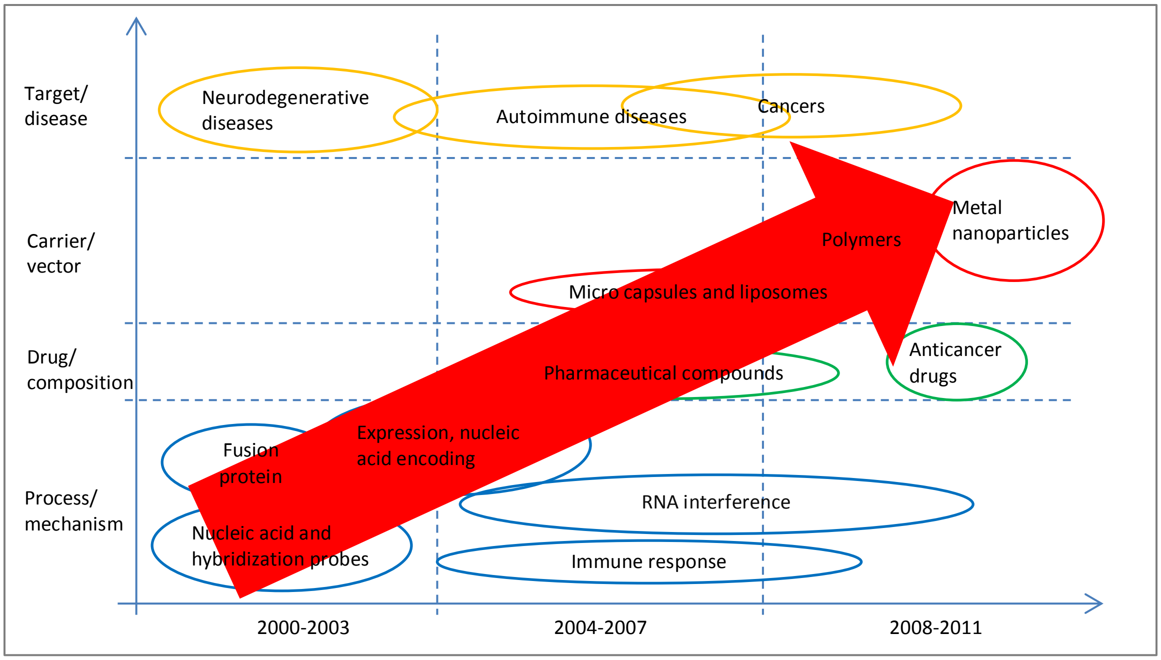

Figure 3. NEDD Developmental Pathways: locating 13 Key Topics
Source: see footnote 11.

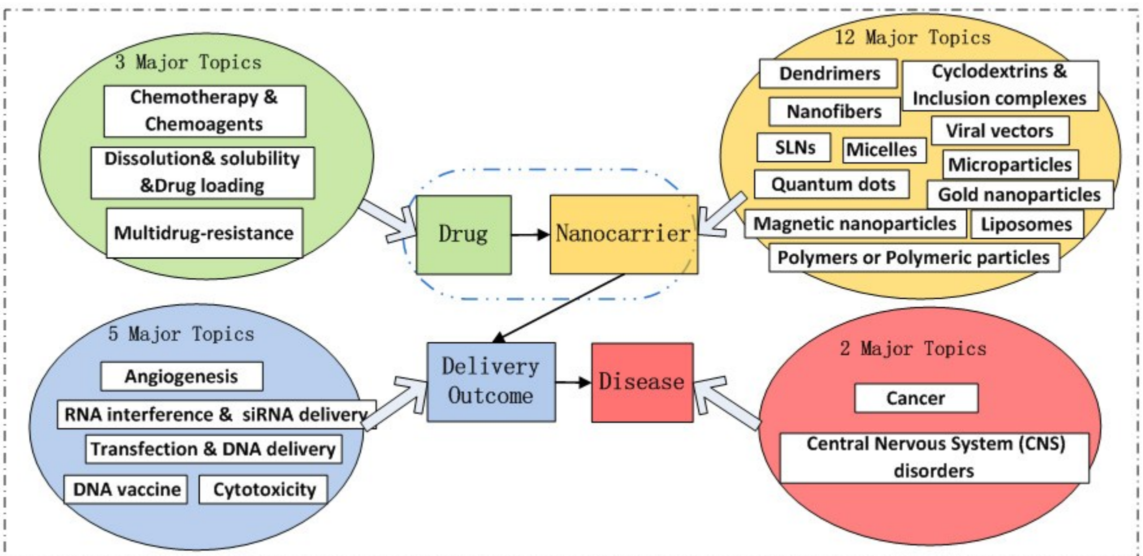

Figure 4. NEDD Sub-Systems
Source: see footnote 11.

# Records	Show Values >= 1 and <= 74 Cooccurrence # of Records	Cisplatin	Methotrexate	Small interfering RNA	Irinotecan	Etoposide	Vincristine	Vinblastine	Carboplatin	Plasmid DNA	Temozolomide	Cyclophosphamide	Bleomycin	Carmustine	Dactinomycin	Everolimus	Ifosfamide	Lomustine	Procarbazine
325	Polyethylene glycol	74	33	15	15	11	15	12	7	16	4	2	6	1	1	1	1		1
96	PLGA nanoparticles	19	5	2	4	8	7	2	2	3	4	2		1					
85	Nanocapsules	18	7	8	2	6			4	1	1		2						
80	Hydrogels/Nanogels	32	11	3	5	3	1	2	3	1	4	2	6	1					
78	Chitosan nanoparticles	11	24	7	2	1	3	1	4		3	5	1	1			1	1	
63	Transferrin/Transferrin receptor	5	3	9		1				9	3			2					
50	Block copolymer micelles	21	9	1	2	5	1		1			1							
48	Albumin nanoparticles	4	15	1		1	1	3	3	1		2		1		1			
45	Solid lipid nanoparticles	7	6	1		5	1	3			2			1			1		
43	Gold nanoparticles	15	6	2	2				1		1				1				
40	Carbon nanotubes	15	5	2	1	2			5	1									
23	Polysorbate 80	2	2								1								
9	PBCA nanoparticles	2					1				1	1							

Figure 5. Connections between NEDD delivery technologies and drugs to treat Brain Cancer
Source: see footnote 11.

A natural extension has been to explore aspects of "convergence" – the interplay of nano, bio, information, and cognitive technologies. Another direction we are pursuing is to devise indicators of technical emergence.

We also experimented with new visualization methods. This work on visualization was aided by a separate but related grant we received from NSF to develop visualizations, including science overlay maps and patent overlay maps, to understand cross-disciplinary research knowledge interchanges Figure 6 shows a recent science overlay map[20 21 22 23] for nano. An earlier nano science overlay map was complemented with one showing the fields upon which nano WoS papers draw most heavily.[24] A co-citation map sharpened understanding of the social science domains contributing to nano (Figure 7).[25]

[20] Leydesdorff, L. and Rafols, I. (2009) A Global Map of Science Based on the ISI Subject Categories. *Journal of the American Society for Information Science and Technology*, 60(2), 348-362.

[21] Rafols, I. and Meyer, M. (2009) Diversity and network coherence as indicators of interdisciplinarity: case studies in bionanoscience, *Scientometrics* 81(2) in print. DOI 10.1007/s11192-009-0041-y.

[22] Rafols, I., Porter, A.L., and Leydesdorff, L., Science overlay maps: A new tool for research policy and library management, *Journal of the American Society for Information Science & Technology*, 61 (9), 1871-1887, 2010. DOI: 10.1002/asi.21368.

[23] For the latest version of the science overlay map process, see: http://www.leydesdorff.net/overlaytoolkit/.

[24] Porter, A.L., and Youtie, J., Where Does Nanotechnology Belong in the Map of Science? *Nature-Nanotechnology*, Vol. 4, 534-536, 2009.

[25] Shapira, P., Youtie, J., and Porter, A.L., The emergence of social science research in nanotechnology, *Scientometrics*, 85(2): 595-611, 2009.

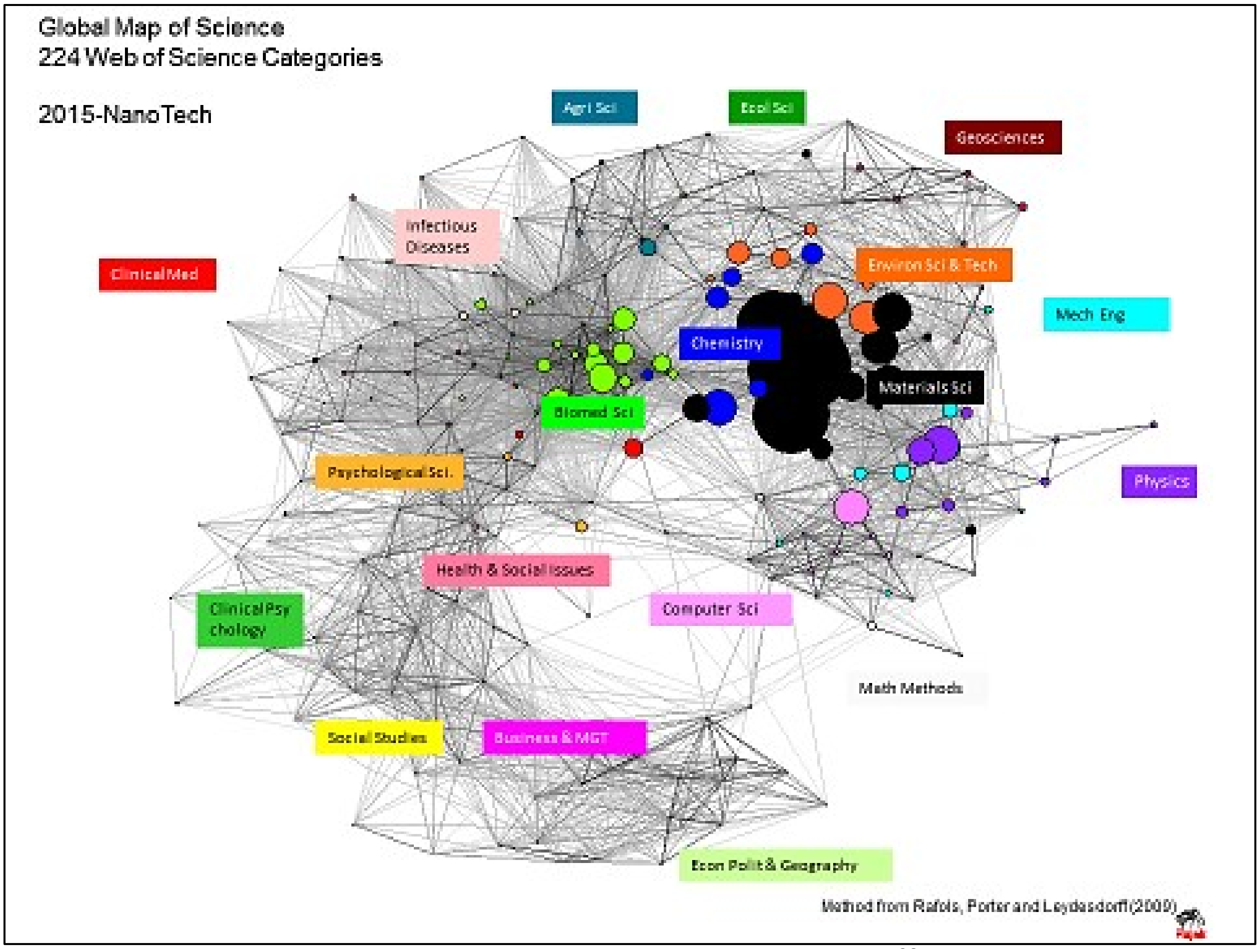

Figure 6. Distribution of Nano Research Publication across Fields for 2015[26]

[Background (black) nodes indicate the Web of Science Categories; map location and connections reflect journal cross-citation patterns for all 2010 science and social science citation index papers. The larger, colored nodes reflect concentrations of nano papers.]

Source: see footnotes 20, 21, 22 and 23.

[26] Kwon, S. (2016) Bibiometric analysis of nanotechnology field development – from 1990 to 2015, presentation to the Southeastern Nanotechnology Infrastructure Corridor (SENIC) meeting, Atlanta.

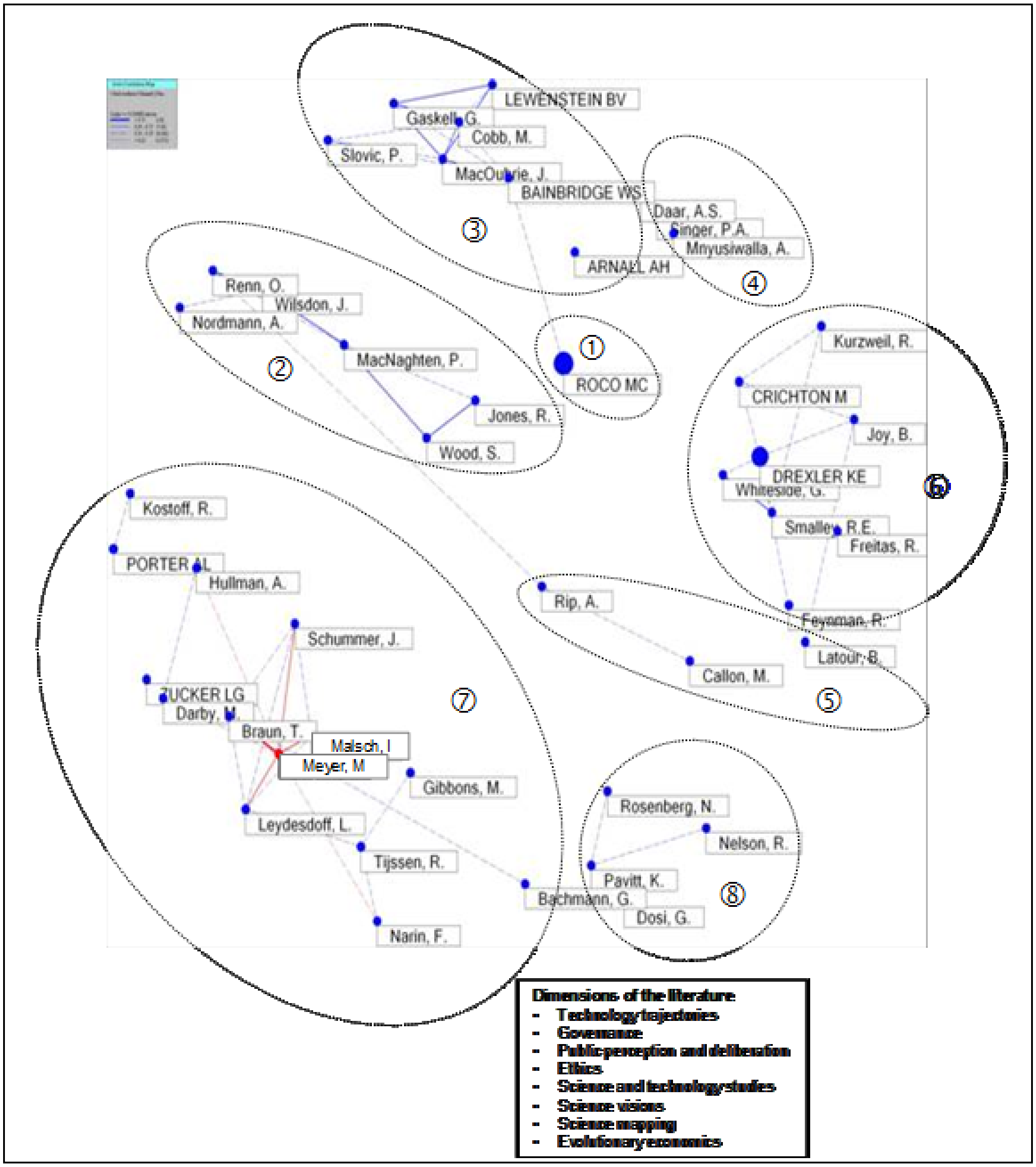

Figure 7. Co-citation Map of Authors Most Cited by Nanotechnology Social Science Articles
Source: see footnote 25.

In addition, we developed methods, in conjunction with colleagues at other universities, for mapping topical areas of publication and patent portfolios using nanotechnology data. Using these methods, we found that graphene applications had a more focused disciplinary orientation, but broader commercialization, while Nano-enabled Drug Delivery (NEDD) displayed the reverse pattern.[27] We

[27] Kwon, S., Porter, A., & Youtie, J. (2016). Navigating the innovation trajectories of technology by combining specialization score analyses for publications and patents: graphene and nano-enabled drug delivery. *Scientometrics*, *Scientometrics* 106 (3), 1057-1071. http://link.springer.com/article/10.1007%2Fs11192-015-1826-9#page-1.

created measures of interdisciplinarity and specialization to complement our visualization efforts. Table 2 compares our "specialization scores" for NEDD and graphene. Figure 8 compares graphene science overlay and patent overlay maps, as appeared in the "Places and Spaces" traveling science mapping exhibit.

Table 2. Relative Specialization of Nano-Enabled Drug Delivery and Graphene Publications and Patents

Technology	**NEDD**		**Graphene**	
Statistics \ Type of Records	**Publication**	**Patents**	**Publication**	**Patents**
Number of Records	**59,798**	**7,796**	**24,381**	**4,340**
Aggregated Specialization Score	**0.12**	**0.51**	**0.30**	**0.15**
Max (Specialization Score)	**1**	**1**	**1**	**1**
Min (specialization Score)	**0.21**	**0.15**	**0.27**	**0.15**
Number of SCs (TIPCs) / record	**1.85**	**7.27**	**1.99**	**2.74**
Publication Year	**2000-2012**	**2000-2012**	**2004-2012**	**2004-2012**
Analysis Coverage*	**97.3%**	**99.8%**	**99.9%**	**99.7%**

* No. of records that have valid Transformed IPC scores or WoS Subject Categories/(total population of publications or patents population of publication or patents)
Source: see footnote 27.

Kay, L., Porter, A. L., Youtie, J., Rafols, I., & Newman, N. (2015). Mapping graphene science and development: Focused research with multiple application areas. *Bulletin of the American Society for Information Science and Technology*, *41*(2), 22-25.

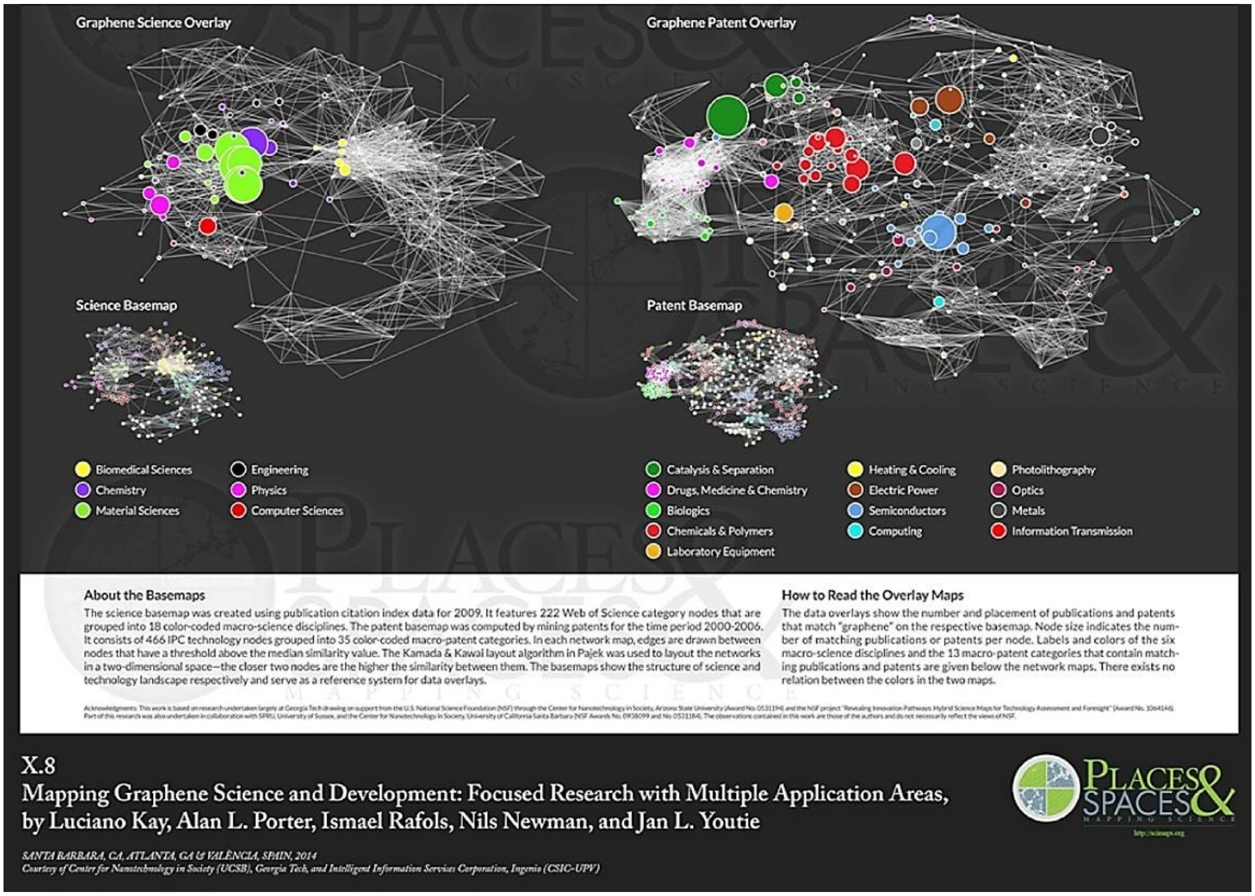

Figure 8. Graphene Science Overlay and Patent Overlay Maps
Source: http://scimaps.org/mapdetail/mapping_graphene_sci_179, accessed June 28, 2016.

Not only did we examine visualizations from a topical standpoint. We also used them to understand geographic patterns of nanotechnology's development. One of the major findings of this work was the rise of China. Our analyses revealed that China, which first surpassed the United States in total number of research publications by 2010 and in the number of citations to these papers by 2013.[28] [See Figure 1.] In examining the factors behind this growth, we found evidence of a "clubbing effect" in Chinese nanotechnology citations, in which the Chinese scholars with the highest citations were more likely to cite other top Chinese scholars. In contrast, their U.S. counterparts were much less likely to cite other top U.S. scholars.[29]

Other geographic-oriented work found that "nanodistricts" in the US and Europe, included most of the leading nanodistricts, are in locations that were prominent in the emergence of earlier technologies. New geographic concentrations of nanotechnology research have also surfaced. However, cluster analysis showed that many of the new regions with research strength were found to lack the

[28] President's Council of Advisors on Science and Technology. 2014 (Oct.). *Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative*. Washington, DC: Office of Science and Technology Policy. [Content contributors: Yin Li, Sanjay Arora, Jan Youtie, Philip Shapira.]

[29] Li Tang, Philip Shapira, Jan Youtie. 2015. Is There a Clubbing Effect Underlying Chinese Research Citation Increases? *Journal of the Association for Information Science and Technology* 66(9):1923-1932. doi: 10.1002/asi.23302

diversity of corporate and other institutional players to likely be able to substantially convert their research into applications [See Figure 9.].[30]

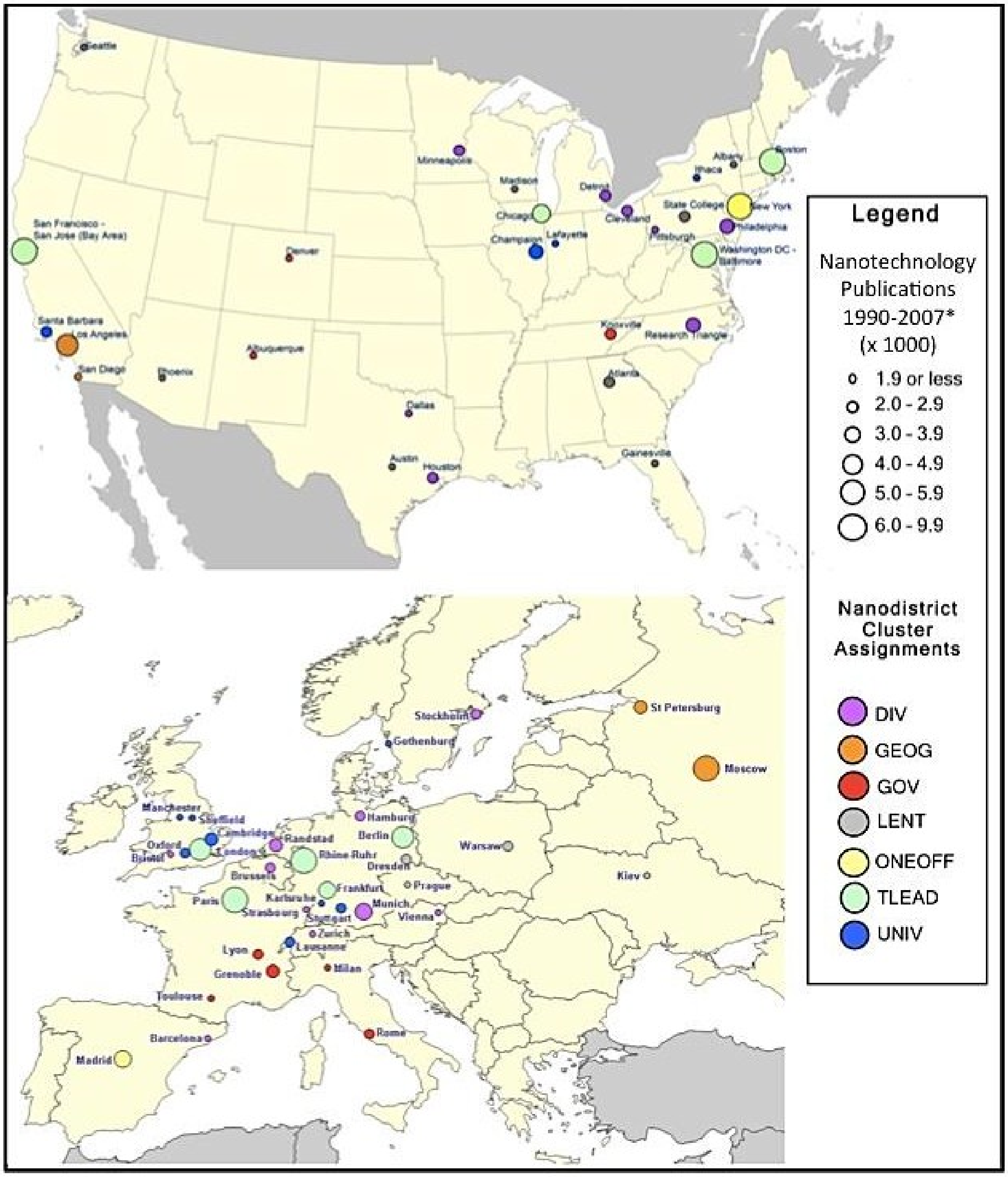

Figure 9. Leading Nanodistricts by Publications and Cluster Type, United States and Europe.
Notes. *Node is at the centroid of the largest city in the area and represents the number of nanotechnology publications in Science Citation Index 1990 to mid-year 2007, based on nanotechnology definition in note 2. Cluster assignments: TLEAD=traditional technology leading clusters; UNIV=university-led areas; GOV=government laboratory/institution led areas; GEOG: geographically-focused cluster; DIV=cluster with some organizational diversity; LENT=late entry clusters; ONEOFF=outlying clusters with distinctive characteristics.
Source: see footnote 30.

[30] Philip Shapira, Jan Youtie, Stephen Carley. 2014 (Dec.). Prototypes of Emerging Metropolitan Nanodistricts in the United States and Europe. *Annals of Economics and Statistics (*Special issue on knowledge capital in nanotechnology and other high technology industries) (115-116):81-104.

While much of these analyses describe the current and past nanotechnology research and commercialization system, we have also pursued “Forecasting Innovation Pathways” for understanding future trajectories of emerging technologies.[31] Forecasting Innovation Pathways entails a combination of analyses of historical trends and patterns, plus efforts to anticipate future trajectories. Forecasting Innovation Pathways links into Technology Roadmapping (TRM). For example, Figure 10 tracks potential solutions to DSSC problems to be overcome, sorting topical prevalence by type (materials, methods, devices) over time. [Ignore details; our intent is to convey the general approach.] As part of this effort to understand the trajectory of emerging technologies, we are pursuing development of “emergence Indicators.” In one application, we investigated “Big Data” research compiled from WoS, tagging 72 “hot topics.”[32]

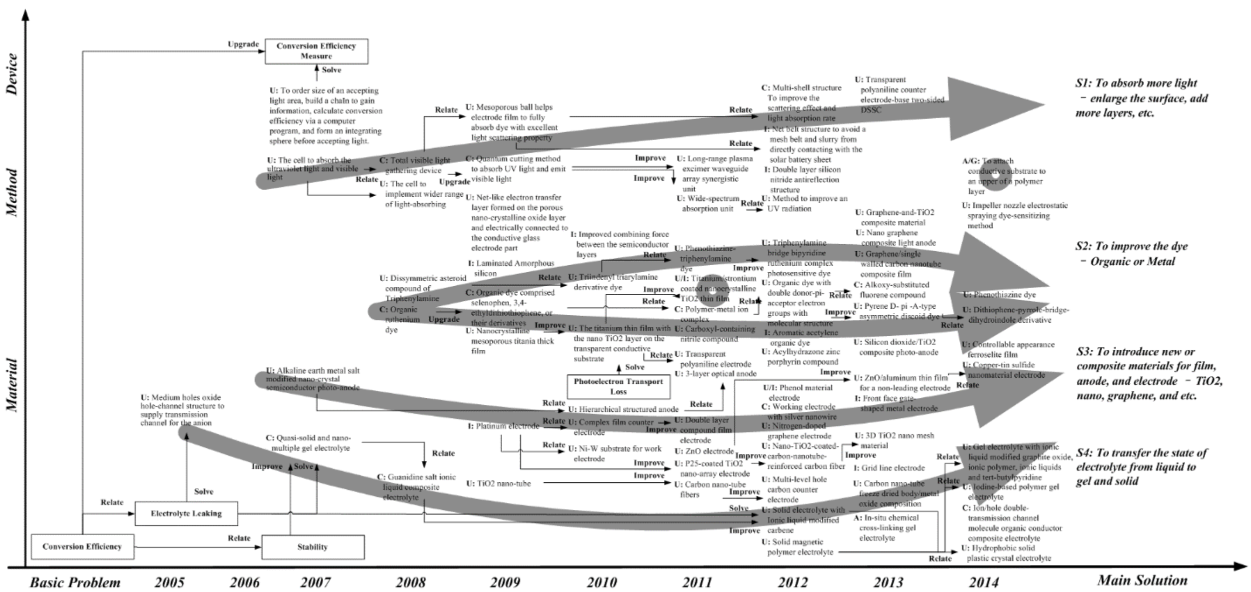

Figure 10. A Problem-Solution Technology Roadmap for DSSCs
Source: see footnote 32.

We have used the knowledge gained throughout our studies of nanotechnology to analyze other emerging technologies. We received a grant from NSF to study the emergence of “big data analytics” and conducted other assessments focused on synthetic biology. In applying methods we developed to study the rise of social science subfields in nanotechnology[33] to the emerging field of synthetic biology, we found that synthetic biology social science research is growing and exhibits connections to its bioethical roots. However, compared with nanotechnology, social science research in synthetic biology gives less consideration to public engagement, bibliometrics and economics, and visionary perspectives.[34]

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[31] Porter, A.L., and Huang, Y. (2016), Forecasting future innovation pathways with big data analytics, *CIMS Innovation Management Report,* 8-13 (July/August), Poole College of Management, NC State University, Raleigh.
[32] Zhang, Y., Robinson, D., Porter, A. L., Zhu, D., Zhang, G., Lu, J. 2016. Technology roadmapping for competitive technical intelligence, Technological Forecasting and Social Change, 110, 175-186, DOI: 10.1016/j.techfore.2015.11.029.
[33] Shapira, P., Youtie, J., & Porter, A. L. (2010). The emergence of social science research on nanotechnology. *Scientometrics*, *85*(2), 595-611.]
[34] Philip Shapira, Jan Youtie, Yin Li. 2015. Social science contributions compared in synthetic biology and nanotechnology. *Journal of Responsible Innovation* 2(1):143-148, doi: 10.1080/23299460.2014.1002123

As noted, this family of studies has utilized desktop text analysis software [VantagePoint – www.theVantagePoint.com[35]] developed especially to help glean useful intelligence from field-structured science, technology & innovation information resources. This software has facilitated development of several novel analytical tools as highlighted through this report.[36] Several of the tools address measurement of interdisciplinarity and cross-disciplinary knowledge transfer[37] on the one hand and technological emergence on the other.

The STIP group had an extensive production of research. More than 70 peer reviewed journal articles were produced by STIP researchers. This output represents a high productivity level of nearly 20 publications per active senior researcher. Several of these works were highly cited, including the initial journal article operationalizing our nanotechnology search strategy. Forty undergraduate and graduate researchers have been involved in STIP research, five of whom received their doctorates. Twenty-four students and faculty from China, Germany, England, and Spain visited and contributed substantially to STIP's nanotechnology research during this period.

Lessons Learned

This paper has discussed the types of strategic information and analyses that a program of a multidisciplinary social science center can produce to enhance the understanding of development of a science-driven technology. The program yielded a number of innovative methods for understanding the emergence of nanotechnology, including webscraping of small and medium-sized company websites, visualizations of patent and publication portfolios and geographic clusters, and methods for understanding innovation pathways.

Five main lessons can be identified that could be useful to other long-term efforts to conduct bibliometric analyses of emerging technologies. These are: (1) the importance of being part of a social science center oriented specifically toward the technology; (2) taking an agile approach to development and maintenance of the bibliometric datasets; (3) having multi-year participation from a core set of graduate students along with visitors from other countries, and multiple team members with diverse networks and collaboration; (4) dedicated space in a non-academic campus building coupled with performance-driven agile management by the STIP principals; and (5) stable long-term funding.

Over this 10-year (plus a no cost extension year) history, we have found that being part of a social science center focused specifically on nanotechnology gave us a special grounding in the technology and its relevance to social science questions. That perspective was less available to investigators working on individual projects in that same domain or being a 'lone' social scientist embedded in a science or engineering center. One example of this concerns our search strategy and datasets. When the center began, many bibliometric researchers were using a simple search term (nano*), which resulted in the exclusion of many scholarly publications that did not yet use this terminology in their work. Moreover, we discovered that the straightforward use of nano* led to the inclusion of papers and patents relating to the compounds NaNO2 and NaNO3 (e.g., papers and patents about fire extinguishers). Another set of bibliometric researchers used overly broad approaches that

[35] VantagePoint development was initiated at Georgia Tech in early 1990's to help exploit science and technology information resources. Search Technology, Inc. and Georgia Tech continued development supported mainly by the Defense Advanced Research Projects Agency (DARPA), the U.S. Army Tank-automotive and Armaments Command, and the U.S. Army Aviation and Missile Command under Contract DAAH01-96-C-R169. The software is also available from Thomson Reuters as Thomson Data Analyzer.

[36] Robinson, D.K.R., Huang, L., Guo, Y., and Porter, A.L. (2013), Forecasting Innovation Pathways for New and Emerging Science & Technologies, *Technological Forecasting & Social Change*, 80 (2), 267-285.

[37] Carley, S., Porter, A.L., and Youtie, J. (2013), Toward a more precise definition of self-citation, *Scientometrics*, 94 (2), 777-780. DOI 10.1007/s11192-012-0745-2.

resulted in a large proportion of records being published prior to the discovery and diffusion of key nanotechnology instruments—the scanning tunneling microscope and atomic force microscope. Yet another set relied on existing nanotechnology publication categories or patent cross-classes, even though it took a while, especially in the case of the patent classes, for these classes to backfill such that they fully represented nanotechnology patents. An independent analysis by Huang and colleagues which compared six nanotechnology search strategies provided further validation of the STIP approach. They found that the results of the STIP search were shown to fall in the middle in size and coverage distribution among these six search strategies.[38]

Concerning the large-scale datasets we used, the STIP team recognized that it would be easy to get bogged down in the storage and maintenance of these datasets. We decided on an agile approach to organizing the datasets which prioritized updating and cleaning through analysis for a given research paper over creating the "perfect" dataset. We used regular desktop computers and networks rather than any specific high capacity computer, with the help of a donation of monitors and a workstation from our corporate partner, IISC. Having an overlapping set of doctoral students who were aware of the structure of these datasets was helpful. Although the students rotated in and out, they tended to be with the STIP group for anywhere from three-to-six years, which provided continuity of knowledge about the datasets.

Human and social capital was very important to the success of STIP. We also learned that graduate students in social science (specifically in the School of Public Policy at Georgia Tech) with "big data" interests and capabilities were much more effective in conducting research using bibliometrics and other text mining tools to understand the development of emerging technologies than were students in the computer science college. It is important to underscore that these students had access to VantagePoint software[39] which enabled them to perform high level cleaning, merging, and visualization of the R&D publication and patent abstract record sets without needing an extensive computer science background.

This cadre of ongoing expertise was supplemented with an influx of visiting researchers, including graduate students and faculty. These visitors came with new ideas and directions that led the STIP team to pursue hot topics and investigate various application areas. Collaborations with CNS-ASU colleagues working with other methods and on other topical areas also resulted in significant publications in the methodology area (e.g., merging medium-scale survey and large-scale bibliometric information), application area (e.g., studying building construction commercialization), and the social science area (e.g., investigating equity and equality issues from a geographic viewpoint). Importantly, the three STIP principals had different networks which enabled relatively rapid and flexible pursuit of new topics relevant to nanotechnology.

This work benefitted from being located in a facility in a new part of campus that was dedicated to commercial transfer of knowledge. The facility had a large dedicated area for student work and a sizable conference room to support regular weekly group meetings. The weekly meetings were an important tool of the three active principals (and co-authors of this paper) to encourage productive work and address any problems in the research team. These principals set and maintained brisk mini-deadlines oriented around the production of peer reviewed journal articles. The principals recognized the importance of having journal articles as the focus, instead of thick final reports, to serve as a driver for moving the analysis of the emergence of nanotechnology forward.

Stable funding also allowed the STIP group to be more creative in developing a search tool and maintaining datasets which might be applied to multiple important policy and management questions.

[38] Huang, C., Notten, A., & Rasters, N. (2011). Nanoscience and technology publications and patents: a review of social science studies and search strategies. *The Journal of Technology Transfer*, *36*(2), 145-172.
[39] thevantagepoint.com

The CNS support for 10 years provided a reliable base for recruiting graduate students and such. This core funding facilitated the acquisition of additional research grants, leveraging those capabilities, to advance methods or pursue particular emerging technology analyses. Likewise, it enabled the group to pursue innovative research areas which would take a length of time to produce results—for example, the webscraping work—while at the same time having other streams of research readily able to yield publications. Maybe this lesson is to be expected, but it is not always easy to implement, especially when, as in the case of the STIP group, the locus of control is at another university. The STIP group spent a great deal of effort making sure that production of journal articles occurred apace, and that government officials and other key stakeholders knew of their work and capabilities. For example, this effort led to the inclusion of STIP information and analyses in two reports for the President's Council of Advisors on Science and Technology (PCAST) in their review of the US National Nanotechnology Initiative.[40]

The methods we developed and findings we reported are now available for testing relative to other emerging technologies. Of course every situation is unique so there likely will be limitations in efforts to generalize these approaches to other emerging technology areas. For example, nanotechnology had less of an entrenched legacy of social science research than do emerging technologies in, for example, the biological sciences.[41] Nevertheless, we hope these methods and lessons can be useful in assessing the bibliometric trajectory of future emerging technologies.

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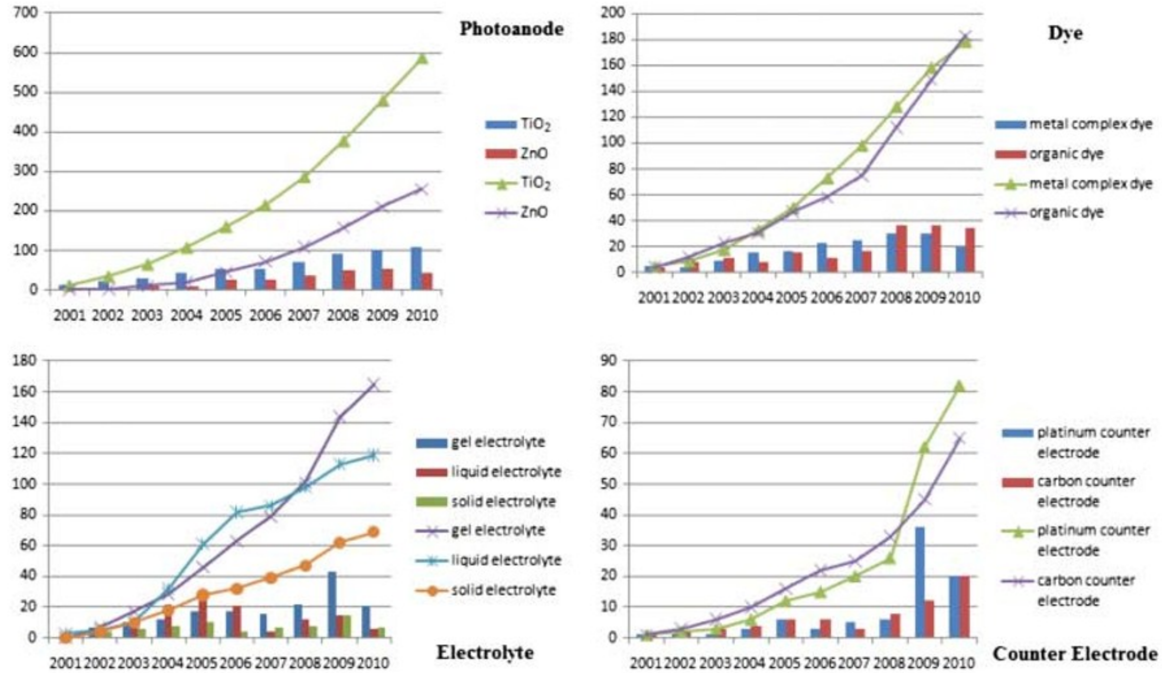
[40] President's Council of Advisors on Science and Technology. 2014 (Oct.). *Report to the President and Congress on the Fourth Assessment of the National Nanotechnology Initiative*. Washington, DC: Office of Science and Technology Policy. [Content contributors: Sanjay Arora, Luciano Kay, Alan Porter, Jan Youtie, Philip Shapira]; President's Council of Advisors on Science and Technology. 2014 (Oct.). *Report to the President and Congress on the Fifth Assessment of the National Nanotechnology Initiative*. Washington, DC: Office of Science and Technology Policy. [Content contributors: Yin Li, Sanjay Arora, Jan Youtie, Philip Shapira].

[41] Shapira, P., Youtie, J., & Li, Y. (2015). Social science contributions compared in synthetic biology and nanotechnology. *Journal of Responsible Innovation*, *2*(1), 143-148.

Appendix – Additional Charts



Source: see note 9.

Nanotechnology Research and Innovation Systems Assessment

Publications associated with the
Nanotechnology Research and Innovation Systems Assessment Group[42]
Georgia Tech Program in Science, Technology and Innovation Policy
School of Public Policy and Enterprise Innovation Institute
Georgia Institute of Technology

Publications: 2007-2016

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[42] The Nanotechnology Research and Innovation Systems Assessment (RISA) Group at Georgia Tech comprises faculty, researchers and students associated with the Program in Science, Technology and Innovation Policy (STIP) of the Georgia Tech School of Public Policy and the Georgia Tech Enterprise Innovation Institute. Nanotechnology RISA Group PIs: Philip Shapira (pshapira@gatech.edu); Jan Youtie (jan.youtie@innovate.gatech.edu); Alan Porter (alan.porter@isye.gatech.edu); Juan Rogers (juan.rogers@pubpolicy.gatech.edu). http://nanopolicy.gatech.edu/. Support for the group's work has been provided by the National Science Foundation (including through awards 1542174, 0531194 and 0937591) and by other sponsors and projects. Many co-authors are associated with other institutions and are not necessarily members of the Nanotechnology RISA Group, although at least one author of every listed publication was a member of the group when the research or publication occurred. This listing is updated through to August 22, 2016.

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Nanotechnology Research and Innovation Systems Assessment Group
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Most Cited Publications
(Top 20 papers by Google Scholar Cites, as of August 17, 2016)

No	Title	Authors	Publication	Year	Citations
1	Is science becoming more interdisciplinary? Measuring and mapping six research fields over time	A Porter, I Rafols	Scientometrics 81 (3), 719-745	2009	347
2	Refining search terms for nanotechnology	AL Porter, J Youtie, P Shapira, DJ Schoeneck	Journal of Nanoparticle Research 10 (5), 715-728	2008	316
3	Science overlay maps: A new tool for research policy and library management	I Rafols, AL Porter, L Leydesdorff	Journal of the American Society for information Science and Technology 61 (9 ...	2010	257
4	Organizational and institutional influences on creativity in scientific research	T Heinze, P Shapira, JD Rogers, JM Senker	Research Policy 38 (4), 610-623	2009	228
5	Assessing the nature of nanotechnology: can we uncover an emerging general purpose technology?	J Youtie, M Iacopetta, S Graham	The Journal of Technology Transfer 33 (3), 315-329	2008	166
6	How interdisciplinary is nanotechnology?	AL Porter, J Youtie	Journal of Nanoparticle Research 11 (5), 1023-1041	2009	133
7	Nanotechnology publications and citations by leading countries and blocs	J Youtie, P Shapira, AL Porter	Journal of Nanoparticle Research 10 (6), 981-986	2008	118
8	Nanopatenting patterns in relation to product life cycle	MSM Alencar, AL Porter, AMS Antunes	Technological Forecasting and Social Change 74 (9), 1661-1680	2007	83
9	Developing nanotechnology in Latin America	L Kay, P Shapira	Journal of Nanoparticle Research 11 (2), 259-278	2009	79
10	Follow the money: What Was the Impact of the Nanotechnology Funding Boom of the Past Ten Years?	P Shapira, J Wang	Nature 468 (7324), 627-628	2010	75
11	Identifying creative research accomplishments: Methodology and results for nanotechnology and human genetics	T Heinze, P Shapira, J Senker, S Kuhlmann	Scientometrics 70 (1), 125-152	2007	71
12	From lab to market? Strategies and issues in the commercialization of nanotechnology in China	P Shapira, J Wang	Asian Business & Management 8 (4), 461-489	2009	67
13	Innovative and responsible governance of nanotechnology for societal development	MC Roco, B Harthorn, D Guston, P Shapira	Nanotechnology Research Directions for Societal Needs in 2020, 561-617	2011	65
14	National innovation systems and the globalization of nanotechnology innovation	P Shapira, J Youtie, L Kay	The Journal of Technology Transfer 36 (6), 587-604	2011	59
15	China–US scientific collaboration in nanotechnology: Patterns and dynamics	L Tang, P Shapira	Scientometrics 88 (1), 1-16	2011	58
16	Where does nanotechnology belong in the map of science?	AL Porter, J Youtie	Nature Nanotechnology 4 (9), 534-536	2009	58
17	Funding acknowledgement analysis: an enhanced tool to investigate research sponsorship impacts: the case of nanotechnology	J Wang, P Shapira	Scientometrics 87 (3), 563-586	2011	53
18	Emergence of Nanodistricts in the United States: Path Dependency or New Opportunities?	P Shapira, J Youtie	Economic Development Quarterly 22 (3), 187-199	2008	51
19	The emergence of social science research on nanotechnology	P Shapira, J Youtie, AL Porter	Scientometrics 85 (2), 595-611	2010	48
20	Capturing new developments in an emerging technology: an updated search strategy for identifying nanotechnology research outputs	SK Arora, AL Porter, J Youtie, P Shapira	Scientometrics 95 (1), 351-370	2013	47